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SEISMIC BEHAVIOUR OF THE I-EXOS SYSTEM DESIGNED BY IH-MADE STRONG MIDDLE SECTIONS

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Abstract

Many countries in the world located in high seismicity zones have old, reinforced concrete (r/c) building stocks with poor seismic performance. The i-EXOS system has been proposed as an effective retrofitting solution for r/c buildings; it consist of a steel truss exoskeleton, connected externally at the building floors and designed to remain elastic during the earthquake (even for the major event) to prevent the building from the formation of the soft-storey collapse mechanism. Within this design objective for i-EXOS, novel Strong-middle Circular Hollow Sections (Sm-CHS) made through the Induction Heat treatment technology appears to be an efficient solution to secure the elastic response of the i-EXOS system. This study performs a computational investigation on the seismic behaviour of a five-storey i-EXOS designed with Sm-CHS and assesses its structural performance under earthquake loads. First, a non-linear finite element model is developed of the steel i-EXOS in the commercial software ABAQUS. Then, the most demanding earthquake displacement time-histories are extracted from a sibling simplified dynamic nonlinear model developed in OpenSEES and induced in the ABAQUS i-EXOS model to assess the seismic response of two design solutions for i-EXOS: (1) the use of conventional steel CHS and (2) the use of novel Sm-CHS. For the conventional design of i-EXOS, it was found that a few members of i-EXOS fail suddenly by buckling although the design has passed the average capacity checks according to Eurocode 8 (EC8) provisions. This indicates the need to further increase the section of the members to ensure stability of the system. On the contrary, the results showed that the design of the i-EXOS using the novel Sm-CHSs can remain almost elastic without experiencing any severe damage under major earthquake events, thus satisfying the design criteria with lighter steel sections.

Keywords: steel exoskeleton, i-EXOS, induction-heat treatment, buckling, seismic retrofit

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1 INTRODUCTION

The majority of existing building stocks consist mainly of reinforced concrete (r/c) framed structures, most of which were built in the second half of the last century [1]. These buildings were designed according to outdated codes, which did not include capacity design principles, and were constructed without proper seismic provisions. As a result, they lack the lateral stiffness and strength that is required to resist seismic forces and often show low dissipative collapse mechanisms, such as soft storey mechanism, with the seismic damage being concentrated in one or a few storeys of the building. To avoid this non-ductile collapse mechanism, the i-EXOS retrofit solution was recently proposed [2-3]; it consists of a suite of steel exoskeletons, eventually equipped with dissipative devices [4], whose members are designed to remain elastic during the seismic event. The system is capable to greatly improve the seismic performance of r/c framed buildings designed to sustain only gravitational loads. Within this design objective for i-EXOS, novel Strong-middle Circular Hollow Sections (Sm-CHS) made through the Induction Heat (IH) treatment technology appears to be an efficient solution to secure the elastic response of the i-EXOS system subject to major earthquake loads.

Recently, IH treatment technology was introduced for large-scale steel structures as a manufacturing process to produce steel members with strengthened zones [5-6]. By utilizing this technology, CHS with a stronger middle length (Sm-CHS) can be fabricated that can offer an enhanced compressive behaviour characterized by an appreciably greater yielding/buckling load and more stable post-buckling response [7-8]. The use of novel Sm-CHS can result in a stronger and more economical design of i-EXOS systems successfully satisfying the quite strict design requirement of elastic design of i-EXOS without increasing the size of steel sections. I-EXOS made of Sm-CHSs may lead to an optimized retrofit solution capable of managing in a cost-effective way the large number of r/c framed buildings that need to be seismically retrofitted. In this paper, a computational investigation is performed to evaluate the effectiveness of this new solution under seismic loads. It is tested on a case building study designed without seismic provisions being representative of the r/c Italian building stock. For this purpose, a nonlinear model of the entire building is developed in the OpenSEES framework [9], to assess the seismic response of the structure, before and after the intervention. Based on the resulting average internal forces, the i-EXOS steel members are iteratively designed to comply with the Eurocode 8 (EC8) [10-11] capacity and stability average checks. Once the cross sections are defined, two detailed finite element (FE) models of the exoskeleton are developed in the software ABAQUS [12] using either conventional steel CHSs or the novel Sm-CHSs. Then, the floor displacement time histories extracted from the OpenSEES models are applied to the nodes of the exoskeleton model developed in ABAQUS. Finally, the improvement due to the IH section treatment is evaluated by comparing elastic buckling loads, hysteretic loops and plastic strains for the two building designs of i-EXOS.

2 DESIGN OF THE I-EXOS MEMBERS

2.1 Description of the i-EXOS system

The i-EXOS system consists of 3D steel trusses applied outside the building, as shown in Fig. 1. Each one includes three types of members: the distant chord (DC), adjacent chords (AC) and diagonals (D), all of them made by circular hollow steel sections (CHS); chords are continuous along the height of the building, while diagonals are pinned at their end. The base of the i-EXOS system is pinned to an isolated plinth. The nodes of the adjacent chords are linked to the building slabs; this connection constrains them to have the same horizontal displacement, while the vertical relative displacements are free. Unlike other traditional exoskeletons, which work adding lateral stiffness to the original scheme, the i-EXOS system forces the drifts to have a uniform distribution along the height of the building, allowing a better exploitation of the deformation capacity of the existing structural elements. I-EXOS system does not transmit forces to the building if the deformed shape induced by the earthquake is linear: in this case, each truss rotates rigidly around the base of the system. Otherwise, if the damage tends to be localized at one or a few floors, the non-uniform distribution of the drift induces internal forces in the truss members, which counteract the localization of the displacement; moreover, the i-EXOS system can mitigate the effects of any irregularities in the distribution of stiffness or mass along the height. This makes the system a solution to avoid the soft storey collapse mechanism. Indeed, after the yielding of structural elements of the weakest storeys, the i-EXOS system forces the members of the rest of the storeys to participate in the global deformation mechanism of the building, thus increasing the lateral resistance of the structure overall and its energy dissipation capacity. The i-EXOS truss system must remain elastic to be effective, so its steel members must be sized not to yield or buckle even for major events.

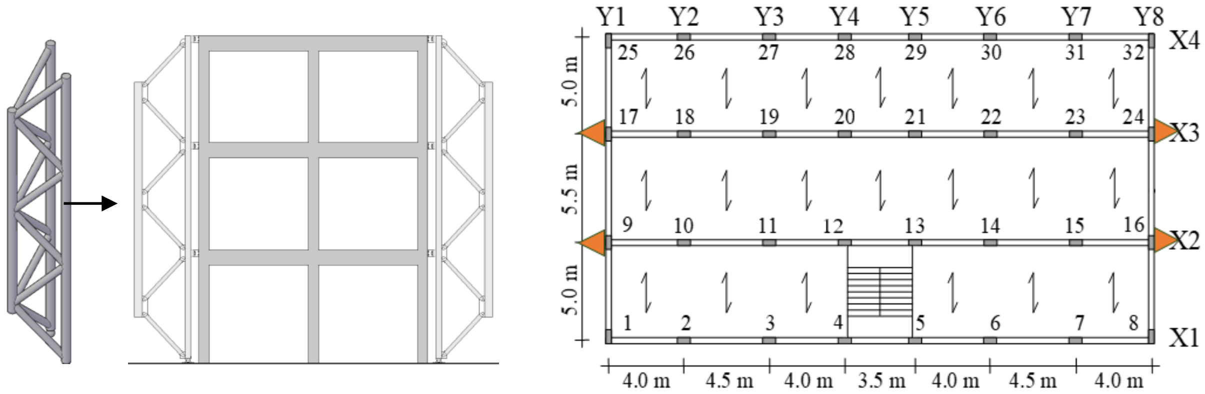

Figure 1: Application of the i-EXOS system and plan layout of the case building study by positioning the exoskeletons (shown in orange) along the X-direction.

2.2 The case study structure

The analyzed structure was intended to represent one typical Italian residential building dating back to the 1970s, before seismic regulations were implemented. Thus, the design follows the old Italian code [13], only accounts for gravitational loads and is based on the allowable stress method. The building is five-storey high, with an inter-storey height of 3.2 m. The floor has a symmetrical rectangular plan, measuring 28.8 m and 15.8 along the X-axis and Y-axis, respectively (Fig. 1). The unidirectional r/c slab has a thickness of 4 cm, with rebars running in the Y-direction; meanwhile, the r/c frames are mainly aligned along the X-direction. As a result, the building exhibits greater lateral stiffness and strength along the X-direction than in the Y-direction. The floors are supported by four seven-bay frames along the X-direction, while two three-bays frames in the Y-direction close the plan layout. Materials used in the design are consistent with the 1970s standards [13], with C20/25 concrete and steel rebar of grade FeB38K. The characteristic compressive cubic strength of concrete is 25 MPa, while the characteristic yield strength of the steel rebar is 380 MPa. The allowable stress values for concrete and steel are 8.5 MPa and 215 MPa, respectively. Axial forces on the columns and distributed loads on the beams are calculated by means of the tributary area method. These forces account for dead loads (g_k) and live loads (q_k); they amount to g_k=5.6 kN/m^2 and q_k=2 kN/m^2 on floor and g_k=4.2 kN/m^2 and q_k=4 kN/m^2 on staircase; the weight of masonry infills is equal to 7.0 kN/m. Columns cross-sectional area is sized based on the axial force, so they decrease along the height. The area of longitudinal rebar in the columns is calculated as the maximum value between 0.6% $A_{c,req}$ and 0.3% A_c, where $A_{c,req}$ and A_c represent the required and actual cross-sectional area, respectively. For the beams, internal forces are computed assuming a continuous beam model. The resulting cross-section of the beams is 30x60 cm at each floor, while the minimum value for longitudinal rebar in tension zone is taken equal to 0.15% of the concrete cross-sectional area. Stirrups with diameters of 8 mm and spacing of 150 mm or 180 mm are used respectively for beams and columns.

2.3 Numerical model in OpenSEES

The seismic response along the X-direction of the building is investigated. Two models are developed in OpenSEES [9] framework to assess the nonlinear response before and after the application of the exoskeletons. Concrete slabs are modeled as rigid diaphragms because of their high in-plane stiffness. Gravitational loads are evaluated combining live characteristic loads by means of a coefficient ψ_2 equal to 0.3 or 0.6 for floors and staircases, respectively; the resulting seismic masses are lumped at each floor center of mass and amount to 220.4 t. Since the rotations of the slabs are negligible, the building is modeled as a train of 2D frames fixed at the base. The nonlinear behaviour of columns and beams is reproduced by means of the *beamWithHinges* element [14]. This element assumes that plastic hinges are concentrated at member ends, while the central part remains elastic. To model concrete cracking, the elastic modulus of the central part of columns and beams is reduced by 50% or 80%, respectively. The plastic hinges at the ends of the members are discretized into fibers with a height of 5 mm, while depth and length are equal to depth and height of the cross-section. The Kent-Scott-Park uniaxial constitutive law ("*Concrete01*") [15] is assigned to concrete, assuming a peak strength equal to the mean value of the concrete strength class and neglecting the effect of the confinement because of the relatively large spacing of stirrups; the tensile strength is neglected. Steel rebars are modelled as single fibres with a kinematic hardening uniaxial constitutive law ("*Steel01*"). Unexpected axial forces, arising in beams because of the rigid diaphragm are avoided by adding at one end of each beam a *zeroLenghtElement* [16] with zero axial stiffness and high shear and flexural stiffness. Each exoskeleton is modelled with an equivalent 2D truss, using an approach already described in [2]; their members are modelled by means of *elasticBeamColumn* or *truss* elastic elements, depending on whether it is a chord or diagonal, and assuming the value of the elastic modulus E= 210 GPa.

2.4 Seismic assessment and design of the i-EXOS members

The seismic performance of the building, before and after the retrofitting, is evaluated by means of nonlinear time-history analyses (NTHA). The seismic input is simulated by a set of 30 artificial ground motions with total duration and length of the stationary part equal to 30.5 s and 7.0 s, respectively [17]. They are compatible with the elastic response spectrum of the EC8 [10] for soil type C and 5% damping ratio; the reference peak ground acceleration (PGA) is equal to 0.35 g on soil type A and simulates the seismic excitation with probability of exceedance equal to 10% in 50 years. The accelerograms are then scaled to a PGA equal to 0.60 g, corresponding to a probability of exceedance equal to 2% in 50 years. The design of the i-EXOS members required to set the position along the façade, the plan dimensions and the number of exoskeletons. As shown in Fig. 1, it was chosen to dispose 2 couples of exoskeletons, whose plan width and depth are equal to 2.0 m and 1.5 m, respectively. The cross sections are designed iteratively to fulfil the EC8 average capacity checks for structures analysed by means of NTHA. The demand to capacity ratios (D/C) on the exoskeleton members are evaluated for each ground motion in terms of Stability Index (SI) and Resistance Index

(RI), based on the provisions set in Eurocode 3 (EC3) [18]. Thus, the target was to obtain for each i-EXOS members an average D/C ratio lower than 1 at a PGA equal to 0.6 g, corresponding to a major event; the significant D/C ratio is chosen as the worst between RI and SI. Each iteration required to choose a set of three cross sections, respectively for AC, DC, D, and to perform the NTHA. Then, the cross-sections are designed based on the obtained average internal forces. The process is repeated until convergence of the cross-sections. The resulting profiles are made of S355 steel CHS, with dimensions of 168.3x5, 273x7.1 and 114.3x5 mm for adjacent chords, distant chord and diagonals, respectively, and the corresponding D/C ratio along the height are shown in Fig. 2b-d. The effectiveness of the intervention is observed comparing the average of the maximum storey drift demands Δ obtained by the 30 ground motions, calculated for the target PGAs. As shown by the red line in Fig. 2a, the frame in its original configuration exhibits for a PGA=0.35 g drift demand at 3rd and 4th storey (2.5% ÷ 2.8%) much larger than that of the other storeys, thus evidencing the formation of a soft storey failure mechanism. When the PGA increases to 0.60 g, most of the analysis terminated because of the response divergence. On the contrary, the retrofitted frame exhibits an almost uniform distribution of the height-wise drift demands, whose maximum value is much smaller than in the original configuration and amount to 1.6% for a PGA=0.35 g. Furthermore, it is notable that i-EXOS lead the frame toward a uniform distribution of drift demand even for a PGA=0.60 g. Thus, the i-EXOS system allows the structure to exploit better its deformation capacity, and this is clearly seen when comparing the blue and red lines in Fig. 2a. The NTHA analyses give a wide range of the D/C ratios on i-EXOS members. As it is shown in Fig. 2b-d with red indicators, some ground motions give a maximum D/C ratio

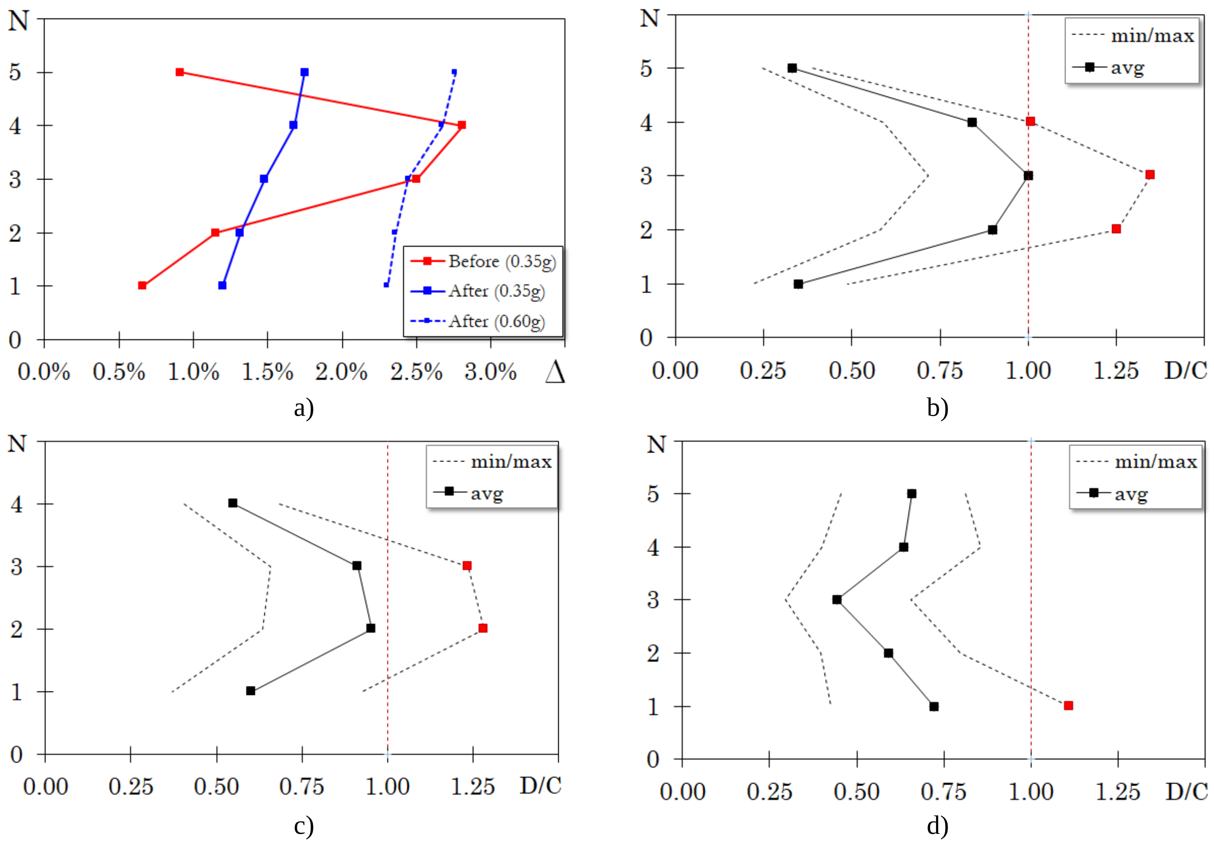

Figure 2: a) Heightwise drift demands for two significant values of the PGA, before and after the intervention. b-d) Heightwise D/C ratios ranges, obtained by means of the NTHA at a PGA = 0.6g, respectively for AC (b), DC (c) and D (d). The continuous line represents the average D/C ratio, while dotted line is for the min/max D/C ratios. Red indicators highlight members whose max(D/C)>1 and, so, chosen to be treated with IH.

much higher than 1, such as 1.35, 1.28 and 1.11 respectively for AC, DC and D. This usually happens for chords in correspondence of the weakest storeys and for diagonals at the base. Furthermore, because of the slenderness ratio of the members, the SI always was the most demanding D/C ratio. It means that there is a certain probability that some members may buckle. However, since buckling is a non-ductile collapse, and static scheme of the exoskeleton is not redundant, it could be a critical issue leading the system to instantly lose its stiffness and effectiveness. Thus, although the average capacity checks are satisfied, the profiles dimensions should be increased to prevent global buckling. On the other side, increasing the cross-sections will also increase the acting axial forces, moreover without a tangible improvement of the r/c frame performance. This may lead to an expensive design just for an event with a very low probability of exceeding.

3 IMPROVING BUCKLING PERFORMANCE OF I-EXOS MEMBERS VIA IH

Improving the buckling resistance of the profiles without increasing its cross-sections would be an optimal solution to meet the design criteria in a cost-effective way. Therefore, the application of the Induction Heat (IH) treatment is utilized in this paper as a strengthening method against buckling following the findings in [7-8].

3.1 Application of the IH treatment to critical i-EXOS members

IH technologies can favourably change the microstructure of conventional steel into a phase-based martensitic microstructure of increased strength locally [5]. It is done by means of a shaped induction coil that, using a high frequency alternating current, heats up the surface of steel sections at a pre-defined temperature. After that, the heated zones are quickly cooled with a water-polymer mixture. This process is cost effective and occurs after the formation of the commercial profile, allowing the treatment of localized areas at original steel section profiles. In this way it is possible to achieve an optimized trend of mechanical properties along the steel profile, according to the structural needs. The IH-treated area of the steel section can benefit from a yield and ultimate tensile strength 2 to 3 times greater than the original ones. Moreover, the impact of residual stress has been found to be small while modulus of elasticity shows a slight change. The i-EXOS members can benefit of the IH treatment to postpone occurrence of buckling by applying the treatment at the middle length of the sections as in [7-8]. This also avoids the localization of high deformation demand at the ends of the sections, in correspondence of the connections, whether they are welded or bolted. As observed in [8] for pinned braces (Fig. 3a), the treated tube with strong-middle CHS (Sm-CHS) could buckle in two different ways, depending on slenderness, imperfections amplitude and yielding strength ratio between section middle and section endsl. The first one has a symmetrical shape, thanks to the formation of a plastic hinge in the middle, and benefits from the increased strength of the IH treated zone. The second one has an asymmetrical shape and benefits of smaller destabilizing effects, due to the smaller amplitude of the imperfections at the plastic hinge, which occurs at the end of the not-treated zone. In this study, the IH treated length is chosen equal to $0.75L_d$, where L_d is the pin-to-pin length (L) depurated of the length involving the connections, assumed equal to 0.05L at each end. The members chosen for treatment are those for which the maximum D/C ratio is greater than 1, as shown in Fig. 2b-d with red indicators.

3.2 Computational modeling of i-EXOS (ABAQUS)

The impact of the IH treatment on the cyclic behaviour of Sm-CHS profiles is evaluated by means of a nonlinear FE model of the i-EXOS built in the ABAQUS software [12]. CHS profiles are modeled using 4 node thin shell elements (S4R). Each tube end has a kinematic

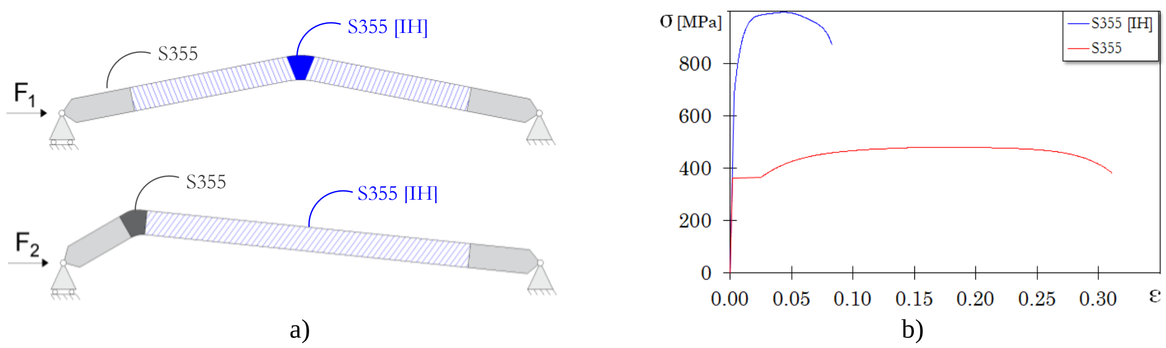

Figure 3: a) failure mechanism due to symmetrical or asymmetrical buckling occurred on a Sm-CHS truss member. b) experimental engineering stress-strain curve resulting from tensile test on 3.2 mm thickness S355 coupon, with and without IH treatment [8].

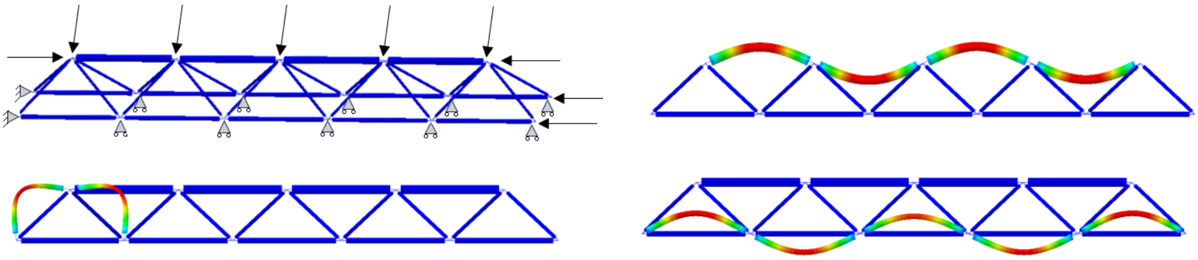

Figure 4: Modified static scheme used for the linear buckling analysis and predominant failure shapes obtained for distant chord, diagonals of the 1st floor and adjacent chord.

rigidity constraint, whose center is connected by means of a weld connector to one end of a rigid beam, whose length is 0.05L. The other beam end is restrained by a weld or pin connector, depending on whether it is a chord or a diagonal, to nodes defined by the intersection of the profiles axis. This modeling approach allows us to simply simulate the different internal restraint of members and the stiffening effect due to connections, which are assumed to be bolted with welded gusset plate. Finite strain theory is assumed for steel materials, while nonlinear geometric effects are also considered because of the large, involved displacements. Material properties are provided by a previous tensile test involving IH-treated and untreated S355 coupons with 3.2 mm thickness, whose results are shown in Fig. 3b [8]. The yield stress is chosen as the average plateau value for conventional steel (360 MPa) while, for IH steel, is obtained by means of the 0.2% offset method (850 MPa). Ultimate strength is equal to 502 MPa and 995 MPa, for conventional and IH steel, respectively. As for the model, a linear elastic isotropic material is assumed until the yield point is reached. For both conventional and IH steel, elastic modulus and Poisson's ratio are assumed equal to E=210 GPa and ν=0.3, respectively. Beyond the yield point, a nonlinear isotropic and kinematic hardening is assumed, with a pressure-independent Mises yield surface. In absence of detailed cyclic test, the nonlinear kinematic hardening calibration is based on a half-cycle unidirectional tensile test with omitted temperature dependency [12]. A sensitivity analysis on the mesh size is performed using the shot-up approach and checking the variations of nodal reactions and buckling loads. A maximum size close to $0.5\sqrt{(Dt)}$ is chosen, where D is the diameter and t the thickness of the tube, which shows a good compromise between computational cost and precision. Once the geometry is defined, a linear buckling analysis is performed on the undeformed configuration of the i-EXOS. Only for this preliminary analysis, additional boundary conditions are considered to avoid the inherent lability of the static scheme. The resulting static scheme and applied unit forces are shown on Fig. 4. The obtained buckling shapes are used to perturb the mesh applying bow imperfection due to the manufacturing process, assuming a maximum amplitude of L/1000. A recent study has shown how the IH treatment can amplify this imperfections amplitude up to twice as much [5]. Hence, to be on the safe side, a doubled imperfections amplitude (L/500) is assumed for the treated members. The concavity of the sinusoidal wave in correspondence of the most stressed span of the chords (i.e. 3rd floor AC and 2nd floor DC) is oriented towards the inside of the exoskeleton, to amplify the axial force effect on the bending moment acting during the worst instant of time (Fig. 4). Ovalization imperfections of the cross-section are neglected as well as residual stresses according to [5]. Once the model is fully defined, the horizontal nodal reactions obtained through the ABAQUS [12] and OpenSEES [9] models are compared. They are observed in correspondence of the adjacent chord nodes linked to the r/c slab, where the floors displacement histories resulting from NTHA of the upgraded OpenSEES model are applied. The considered PGA is 0.15 g, whereby both models are still elastic. Only slightly bigger reactions are observed in the ABAQUS model, because of the added rigid beams, and it confirms the good agreement between the two models.

3.3 Seismic performance assessment of i-EXOS

Once the i-EXOS ABAQUS model is validated, many imposed displacement history analyses are performed using the dynamic implicit solver, involving the models with and without IH-treated members. For this purpose, 2/30 ground motions are identified as responsible for the highest maximum D/C ratios on chords and diagonals of the OpenSEES model. Thus, the resulting floor displacement histories, provided by NTHA carried out with OpenSEES at a PGA=0.60 g, are assigned to the corresponding nodes of the ABAQUS model. The improvement due to the IH treatment is observed on the most critical elements: 1st storey diagonal, 3rd storey adjacent chord and 2nd storey distant chord. It was found that the selected combination of IH-treated length, material strength, imperfections amplitude and members slenderness, always enables the middle length of the novel Sm-CHS profiles to remain elastic. Hence, in this study plastic hinges always occur at the ends of the untreated length.

As shown in Fig. 5, the CHS diagonal is subjected to large plastic strain demands. The global buckling occurs for an elongation equal to -0.13%, corresponding to a buckling load $N_{b,D}$=533 kN. Then, a quick degradation of the strength is observed until the maximum elongation (-1.11%). After this point, the diagonal cannot recover its strength and reaches a post-buckling load equal to 0.35$N_{b,D}$. The post-elastic stiffness is compromised and the residual elongation increases for each cycle. At the end of the analysis, the equivalent plastic strain (PEEQ) in the middle section is equal to 7%. Conversely, the Sm-CHS diagonal exhibited a better behaviour. Indeed, even if buckling occurs for similar axial load and strain values, it shows only a slight decrease of strength. The plastic strain demand is much lower and localized in two points instead than one, with PEEQ equals 2.5%. This allows the truss to show a post-elastic stiffness equal to the elastic one and only a minor residual strain (-0.03%). On the adjacent chords, the effect of the IH treatment differs because of the continuous scheme. As shown in Fig. 6 for the adjacent chord made of conventional steel, global buckling occurs for an elongation equal to -0.16%, corresponding to a buckling load $N_{b,AC}$=823 kN. After the occurrence of global buckling, it has a lower degradation of strength (-15%) and stiffness. Despite this fact, large plastic strains occur again in the middle section due to local buckling; here, PEEQ=3.6% at the end of analysis. The large deflection in the middle part of the member negatively affects the buckling load, because it contributes to increasing the bending moment at the span ends. Conversely, the Sm-CHS AC shows a lower deflection in the middle, because of the elastic behaviour of the middle length, and it leads to an 11% higher buckling load, $N_{b,AC}$=912 kN. After buckling, no strength degradation was observed. Moreover, the residual elongation is smaller (0.78% vs 1.85%) and the post-elastic stiffness is unchanged. The DC shows the smallest improvement gained by IH treatment. After an earlier yielding in tension, the buckling load only slightly increases (+4%). At the same time, a larger PEEQ in correspondence of the plastic hinges was observed (4.2% vs 1.5%), as shown in Fig.7. Since it has a low normalized slenderness (λ=0.45), earlier remarks are confirmed [8].

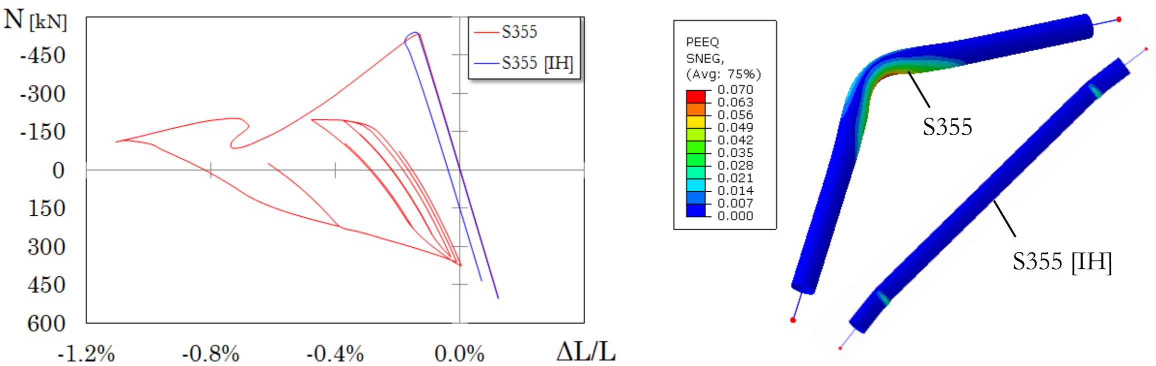

Figure 5: Axial Force-Elongation loops and final PEEQ strains (1st storey upper diagonal)

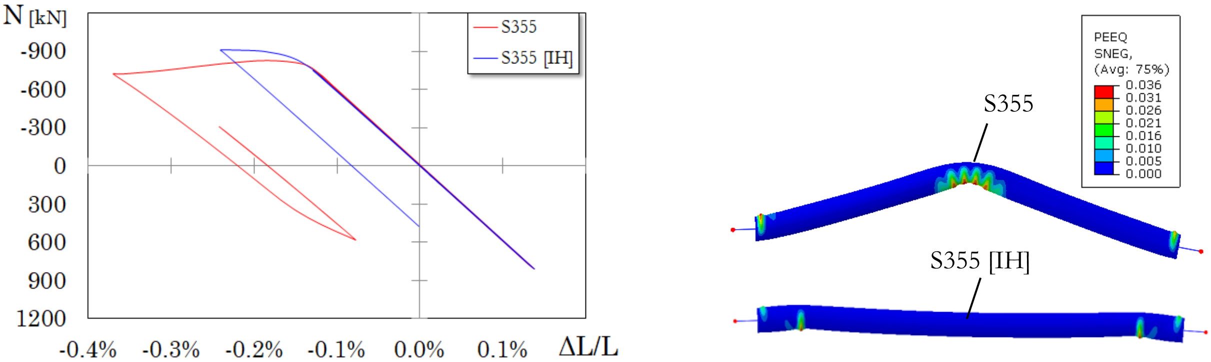

Figure 6: Axial Force-Elongation loops and final PEEQ strains (3rd storey adjacent chord)

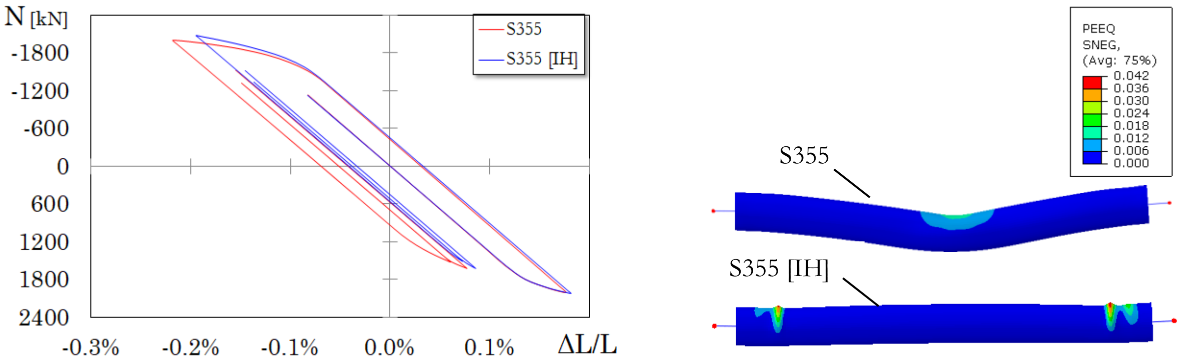

Figure 7: Axial Force-Elongation loops and final PEEQ strains (2nd storey distant chord)

4 CONCLUSIONS

- This paper examines an application of the IH treatment to CHS profiles belonging to i-EXOS retrofitting systems. Buckling performance under seismic loads of both conventional and IH-treated members are compared. For this purpose, a computational study based on previous experimental tests on conventional and IH-treated steel materials was conducted.

- Firstly, the design of the i-EXOS system was made referring to a case study representative of a common existing r/c building. For this purpose, an OpenSEES global model was developed. The design met the criteria set in EC8. Indeed, the analysis of the response averaged over the 30 ground motions shows that i-EXOS can guarantee uniform distribution of storey drift along the height and the average stability index (SI) of i-EXOS members never exceeds the value of 1. However, in occurrence of some very demanding ground motions, some members of i-EXOS may experience buckling. Hence, the design was improved by applying the IH treatment in the middle length of the members, instead of increasing the dimensions of the cross-section. The resulting exoskeleton was studied by means of a refined nonlinear finite element model built in ABAQUS software.
- It was found that some conventional CHS profiles buckle early, suffering from severe damage. The comparison of the ABAQUS models of IH-treated and untreated i-EXOS shows that the IH treatment of the middle length of the steel section (Sm-CHS) can effectively improve the response of i-EXOS members. Indeed, even considering the most demanding ground motion, the IH-treated members of the i-EXOS exhibited very limited nonlinear behaviour. The effectiveness of the same treatment depends on the end constraints and slenderness ratio of the truss members. On tested profiles, the treatment generally increased the bucking strength (up to 11%). Furthermore, it improved the post-buckling behavior; indeed, the treated members did not suffer the stiffness and strength degradation that characterized members made of conventional steel.
- The design made using Sm-CHS profiles appears to be a promising way to successfully satisfy the design criteria set for the i-EXOS system, allowing its elements to remain almost elastic (as required) using lighter steel sections.

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